STUDY OF NEUTRINO BACKGROUND FOR THE LOW-MASS DARK MATTER SEARCH IN FUTURE NEUTRINO EXPERIMENTS

by

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ABSTRACT

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With high-intensity neutrino beams and large mass detectors, neutrino physics has entered the high precision measurement era. Accelerator experiments that use high-intensity proton beams impinging on a fixed target could produce dark matter along with neutrinos. DUNE, one of the most extensive neutrino experiments under construction, has similar prospects of looking for low-mass dark matter (LDM) produced in the proton interactions with the target. With the possibility of charge-neutral LDM production in the target, numerous neutrinos will be generated alongside it, which will be the primary background to the LDM signal. To understand these neutrino backgrounds, we studied two “modified DUNE” frameworks: Neutral Rich Horn Focusing (NRHF) System and Targetless DUNE. These systems help us reduce background neutrinos in search of LDM

signals. These configurations also enhance the signal-to-background ratio by several orders of magnitude.

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CHAPTER 1

INTRODUCTION

1.1 Standard Model

One of the primary motivations of high energy physics is to develop mathematical expressions or a theory that unifies all four known forces in our universe. It is also known as the theory of everything. The closest thing we have right now to the theory of everything is the Standard Model (SM) of particle physics. This theory is a unification of electromagnetic, weak, and strong interactions (excluding gravity) and accounts for all the known elementary particles. Ignoring some phenomena, the model has been able to stand its ground to different tests and predicts various properties in particle physics with high accuracy.

This model can be divided into two groups: Fermions (matter particles) and Bosons (force particles). Fermions contain all the elementary particles, so they are the building blocks of our cosmos. Fermions can be further divided into two types: quarks and leptons. Quarks make protons and neutrons, while leptons include electrons and neutrinos with their flavors. The quarks interact with the electromagnetic, strong, and weak forces, while the leptons only interact with weak force and electromagnetic force when charged. Each group has six particles. The lightest and most stable particles make up the first generation, whereas heavier and less stable particles make up the second and third generations.

Bosons are force carriers, and there are four of them. They are gluon, photon, and Z and W bosons. Gluon carries strong force, whereas photon carries electromagnetic force.

Z and W bosons, on the other hand, carry weak force. There is one more theorized force carrier called "graviton." Theoretical physicists have predicted that "graviton" is associated with gravity just like other bosons associated with each force. However, no one has been able to detect it yet.

There is one more critical aspect of the theory: the explanation of how particles acquire mass. This extension of the theory is known as the Higgs mechanism. The Higgs field is a fundamental field responsible for giving mass to the particles. The more the particles interact within this field, the heavier the particles become. When the Higgs field is excited enough, the particle emerges from it. Theorized in 1964 and confirmed in 2012, the field and particles are named Higgs Field and Higgs Particle. Here is a picture of particles grouped together in the SM.

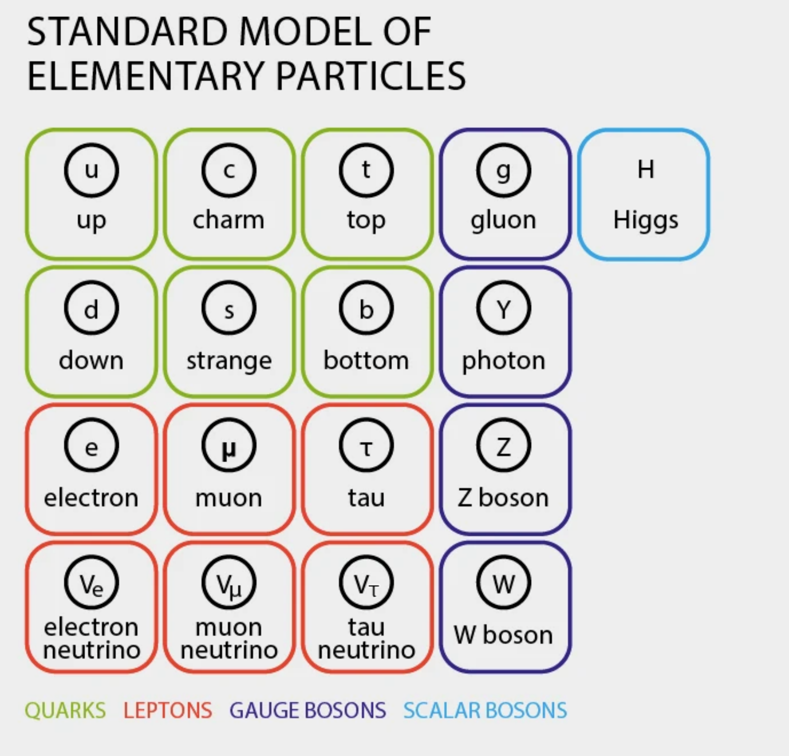

Figure 1.1: Elementary Particles of the Standard Model

1.1.1 Limitation of Standard Model

Though one of the most successful scientific theories of all time, the SM has its deficiencies as it cannot unfold certain observations of our physical world. Some of the unexplored phenomena by this theory are as follows:

a) Gravity.

Even though gravitational force is one of the most fundamental and well-tested forces in nature, the SM cannot explain it. There is a possibility of the existence of particles called gravitons which could act as a force carrier for gravity; however, we have not been able to detect it yet. To put it simply, we still have no idea what gravity is.

b) Dark Matter and Dark Energy.

Dark matter makes up 85 percent of all the matter in our universe [1], while dark matter and dark energy comprise more than ninety-five percent of the matter-energy content of our universe. However, the SM does not account for dark matter or dark energy. Only five percent of our cosmos is described by the SM, while the rest of our universe is unknown to us.

c) Neutrino Mass

The SM predicated that the neutrinos do not have any mass. However, in 1988, the SuperKamiokande collaboration announced the evidence of neutrinos mass [2] for the very first time. With the single-handedness of neutrinos, we know they do not acquire their mass through the interaction with the Higgs field. Hence, the mass of the neutrino is unexplained by the SM.

d) Matter-Antimatter Asymmetry.

According to the Big Bang theory, there should have been an equal amount of matter and antimatter present at the beginning of our universe. However, when we observe today, we find that we live in a profoundly matter-dominated world. Given the nature of matter and antimatter, how did matter manage to survive this primeval annihilation? Also, where did the corresponding antimatter go? These questions are not answered by the SM either.

1.2 Neutrinos

Neutrinos are one of the elementary particles that only interact through weak force and gravity. It is also notoriously known as a ghost particle for its nature of rarely interacting with normal matter. They are special in that they have a neutral charge, do not feel the strong interaction, and are lighter than other particles by several orders of magnitude. At any given moment, there are billions of them passing through us without any form of interaction.

As for history, the neutrino was proposed by Pauli in 1930 to preserve the law of energy conservation in nuclear beta decay.

$$n \longrightarrow p^+ + e^- + \bar{\nu}_e$$

He also gave us a model based on Dirac's quantum field theory of electromagnetism for the beta decay process. The experimental confirmation came in 1956 from the results produced by Reines and Cowan [3] when an antineutrino was detected in a Savannah River nuclear reactor in South Carolina.

The study of neutrinos is one of the ways to extend our current model and dive into the Beyond the Standard Model (BSM) world. For instance, as discussed previously, the

SM predicted neutrinos to be massless; however, phenomena such as neutrino oscillation, where one neutrino flavor changes into another as it travels, indicate neutrinos have mass. Additionally, the helicity of neutrinos implies that they do not obtain their mass through Higgs interactions like the rest of the particles. Thus, how do neutrinos acquire their mass?

Charge-conjugation and parity-reversal (CP) symmetry violations have already been observed in the quark sector through the decays of neutral kaons [4]. However, the numbers were too small to account for the matter-antimatter asymmetry observed in our universe. Hence, physicists are looking for CP violations in the lepton sector, which could create the matter-antimatter disparity by leptogenesis [5]. Neutrinos could help us answer this asymmetry problem as CP violations could be measured between oscillations of muon neutrino to electron neutrino and the oscillation between their corresponding antineutrino [6].

With that, neutrinos studies could help us understand the mass hierarchy in elementary particles, the relation between helicity and mass, and more. It will take us a step closer to understanding our universe beyond our current model.

1.3 Dark Matter

Dark matter is perceived to make up about 85 percent of the mass in the entire universe. It is a compelling observational motivation in searching for new physics since the SM of Particle Physics cannot explain its existence. Different experimental techniques of direct detection, indirect detection, and collider technique have been proposed to search this hypothetical form of matter. Out of many models, one of the possible ways to look for MeV-scale dark matter is in large-scale accelerator-based experiments. With such possibilities, some of the few leading accelerator-based experiments for LDM are Search for Hidden Particles (SHiP), Light Dark Matter eXperiment (LDMX), and Beam Dump eXperiment (BDX).

Some of the observational evidence of the existence of dark matter are as follows.

a) Galaxy Clusters:

For massive objects such as stars swirling in space, the gravitational pull of the galaxy should be strong enough to hold them together in the cluster. The greater the stars' kinetic energy, the higher the gravitational pull should be to balance the system's total energy and keep them intact. Studies of galaxy clusters show that there is not enough mass to even out the average kinetic energy of the system. This hints at the presence of some hidden mass that is keeping those clusters bound.

b) Galactic curves:

The luminous mass density of galaxies decreases as we move away from the galactic center. From the classical mechanics, we know that the rotation velocity decreases as we go further from the center of mass. This is the expected result that can be observed in our solar system as well. However, this is not the case while studying different galaxies. The velocities of stars remained constant as we advanced away from the galaxy’s center. These movements of stars in spiral galaxies indicates there should be some undetected mass (dark matter) in the universe to explain this discrepancy.

c) Gravitational lensing:

General Relativity explains gravity as a geometrical representation of space and time, a curvature of space. A massive object, such as a galaxy cluster, acts like a lens by curving the space between a light source and an observer such that the light's path will bend around it. The more massive the objects, the stronger the lensing that occurs. The technique to measure masses of galaxy clusters without depending on dynamics, such as velocity observations, is called gravitational lensing.

Through gravitational lensing, we can learn about the curvature of space due to mass. A study of mass-to-light ratios in different clusters suggests the missing mass of our universe.

CHAPTER 2

DEEP UNDERGROUND NEUTRINO EXPERIMENT (DUNE)

2.1 Working Mechanism

Deep Underground Neutrino Experiment (DUNE) is one of the most extensive scientific experiments on US soil. The central theme of this experiment is to consider the patterns of neutrino oscillations, which may indicate charge conjugation and parity symmetry (CP) violations, as well as the study of proton decay. DUNE consists of two massive neutrino detectors. The first one is called DUNE Near Detector (ND) located in the Fermi National Accelerator Laboratory (FNAL) in Illinois. It will record the particle interaction near the source of the beam. The second (bigger one) is called the DUNE Far Detector (FD), located one mile underground at Sanford Underground Research Facility in Lead, South Dakota.

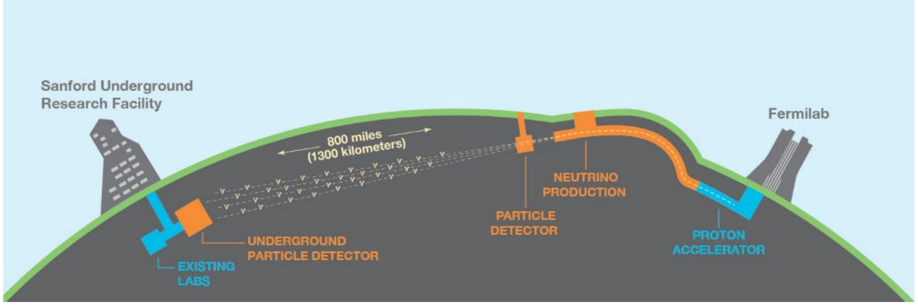

Figure 2.1: Overview of DUNE Framework

The neutrino beam production process starts with a highly energetic proton beam of around 120 GeV produced in Fermilab’s largest accelerator. These protons beams will impinge on the fixed carbon target (graphite). The interaction between graphite nuclei and protons will produce different species of particles, such as charged pions ($\pi^{\pm}$), neutral pions (π^{0}), eta (η), kaons (K), electrons (e^{-}), and highly energetic photons (γ). These particles will be focused on a decay pipe using magnetic horns. As they travel through the decay pipe, most of them will decay or be absorbed. On the other hand, charged pions will undergo two-body decay in flight, resulting in muons (μ) and neutrinos (ν). Since the muons are charged and leave traces of energy in normal matter, they will be absorbed in the beam dump while the neutrinos will pass through it as they have low cross-section. In this way, we can create a neutrino beam of high purity through proton-carbon interactions.

Some of these neutrinos will hit the ND and continue traveling another 800 miles where FD will be waiting for them. During this time, neutrinos will oscillate from one of its flavors to another. By analyzing the data produced between these two detectors, we hope to understand the phenomena of neutrino oscillation.

As we have entered the high precision measurement era, it is an amazing time to study these elusive particles as neutrinos could answer several fundamental questions about the nature of matter and the universe.

2.2 Search for Low-mass Dark Matter in Neutrino Beam

Looking at DUNE from a BSM perspective, the highly energetic photons produced in proton-carbon (graphite target) interaction can also have LDM as a final product. Through processes, such as Drell-Yan, bremsstrahlung, cascade photons, and meson decay in combination with the kinetic mixing with the SM photons, dark photons could be produced, which decay to create a pair of Low-mass Dark Matters (LDM) [7-11]. With that, we can search for LDM through signatures of their scattering with electrons or nuclei in the detector.

For the LDM search in DUNE, the large number of neutrinos will act as a significant background to the LDM signal since their interactions in the detector are identical to those of the SM, resulting in virtually the same signatures. In other words, the neutrinos signature can mimic the DM signal.

Since DUNE’s primary focus is neutrino physics rather than LDM searches, we modified its framework to minimize the neutrino production for background-free LDM signals. The two structures we studied were the Neutral Rich Horn Focusing (NRHF) system and Targetless DUNE.

CHAPTER 3

NEUTRAL RICH HORN FOCUSING (NRHF) SYSTEM

3.1 Working Mechanism

The primary motivation behind this system is to reduce background neutrinos for LDM searches in the detector. It also allows the co-existence of beam dump-style experiments for dark matter searches and precision neutrino experiments. The working mechanism of the NRHF system is similar to that of DUNE, with the addition of a sign-selecting 3D dipole introduced to divert charged particles into the neutrino experiment sector.

The accelerator, such as in DUNE, drives the proton with high intensity and smashes it into the target (graphite). These protons will collide with the nuclei of the target and produce other subatomic particles, like charged pions ($\pi^{\pm}$), neutral pions (π^{0}), kaons (K), electrons (e^{-}), and highly energetic photons (γ). Here, LDM can be produced by a portal interaction through the conversion of photons into dark photons. Given their different momenta, these secondary particles will move at different scattering angles. Then, the magnetic horn will come in play to make these particles collinear. Eventually, these particles will pass through a sign-selecting 3-D dipole that diverts the charged particles into a neutrino detector and leaves the neutral particles on their way to a beam dump-style experiment for dark matter search. The framework of NRHF system can be visualized as shown below.

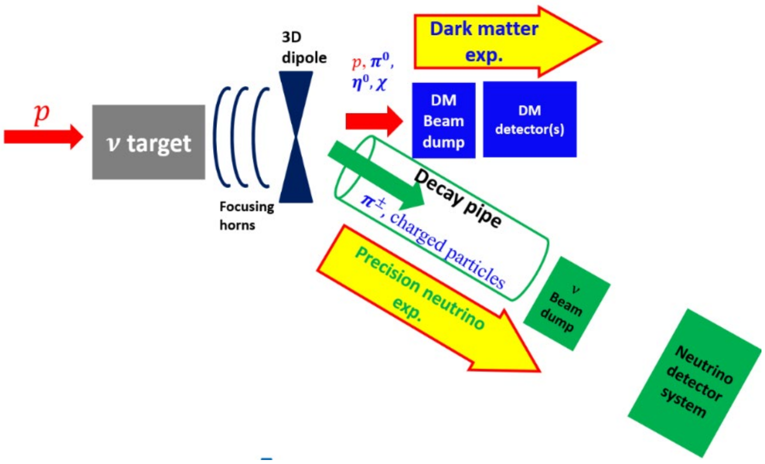

Figure 3.1: Overview of NRHF System Framework

In the neutrino side of the experiment, the diverted charged particles, such as positive pions (π^+), will decay into positive muons (μ^+) and neutrinos (ν). As they pass into the neutrino dump, the muons are absorbed. However, since neutrinos have a low cross-section, they can pass through anything. In this way, we are left with many focused neutrinos (neutrino beams) that will head into the neutrino detector.

In the beam dump-style experiment, the neutral pions will decay into two photons, and these photons have a probability of converting into dark photons. These dark photons annihilate into two dark matter particles. In this manner, both the LDM search and neutrino experiment can be done in the same framework.

3.2 Pions Study

The study of pions is critical as the decay of mother-charged pions determines neutrino flux. On the other hand, pion decay depends on its flight time. Hence, to determine the neutrino production, we derived pions' survival and decay probability.

Some of the formulae used in the derivation are as follows:

1) Fractional speed: $\beta \equiv \frac{v}{c} \leq 1$, where c is the speed of light

2) Lorentz factor: $\gamma \equiv \frac{1}{\sqrt{1-\beta^2}} \geq 1$

3) Rest mass energy of a particle with mass m_0: m_0c^2

4) Total energy of a particle of mass m_0: $E_{tot} = \gamma m_0 c^2$

5) Dilated lifetime of a particle of lifetime τ_0: $\tau' = \gamma\tau_0$

Now, the time of flight of pions can be written as,

$$t_{\pi^\pm} = \frac{L}{\beta_{\pi^\pm}\, c} = \frac{E_{\pi^\pm}}{\sqrt{E_{\pi^\pm}^2 - (m_{\pi^\pm}c^2)^2}}\frac{L}{c}$$

where, L is the distance between a neutrino target and the 3D dipole

$E_{\pi^\pm}$ is the energy of charged pions.

Assume $E_{\pi^\pm} \approx 2E_\nu$,

$$t_{\pi^\pm} \approx \frac{2E_\nu}{\sqrt{4{E_\nu}^2 - (m_{\pi^\pm}c^2)^2}}\frac{L}{c}$$

Now, the probability of survival of charged pions can be written as,

$$p\,(E_\nu) = \exp\left[-\frac{t_{\pi^\pm}}{\gamma\tau^0_{\pi^\pm}}\right] = \exp\left[-\frac{2E_\nu}{\sqrt{4{E_\nu}^2-(m_{\pi^\pm}c^2)^2}}\frac{m_{\pi^\pm}c^2L}{\tau^0_{\pi^\pm}c}\right]$$

we know, $m_{\pi^\pm}$ = 0.14 GeV/c^2 and $\tau_{\pi^\pm}$ = 2.6x10^{-8} sec

$$p\,(E_\nu) = \exp\left[-\frac{0.018\,L}{\sqrt{4{E_\nu}^2-(0.14)^2}}\right] = \exp[-b(E_\nu)L]$$

where b $(E_\nu) = -\frac{0.018\,L}{\sqrt{4{E_\nu}^2-(0.14)^2}}$ is a boost factor.

Similarly, the decay probability of charged pions can be written as,

$$1 - p\,(E_\nu) = 1 - \exp\left[-\frac{0.018\,L}{\sqrt{4{E_\nu}^2 - (0.14)^2}}\right] = 1 - \exp[-b(E_\nu)L]$$

From the survival probability of pions, we can estimate the neutrino flux on the neutrino experiment side. In contrast, the decay probability of pions will help us determine the background neutrinos for the LDM search.

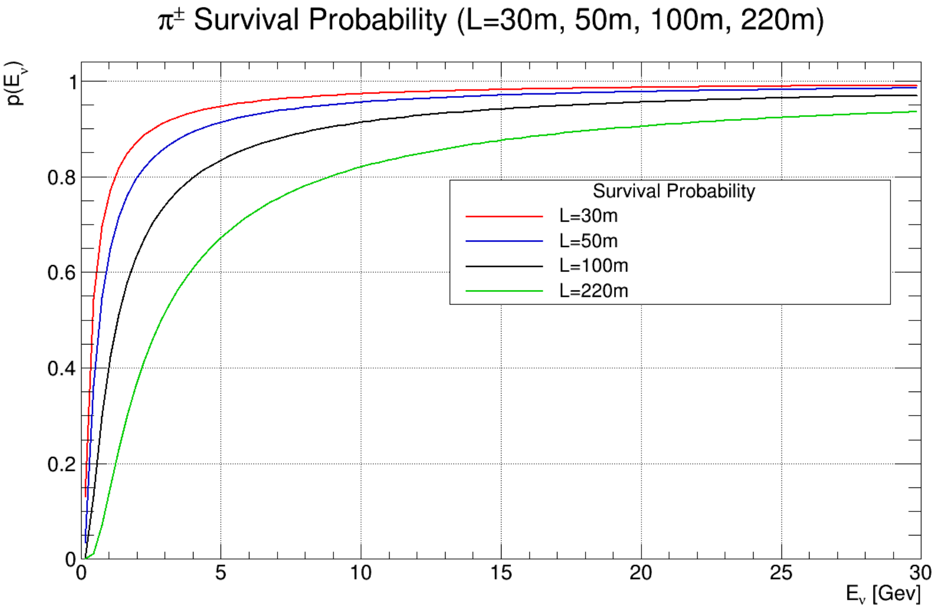

Figure 3.2: Comparison of survival probability of mother-charged pions for various distances between the target and 3D dipole

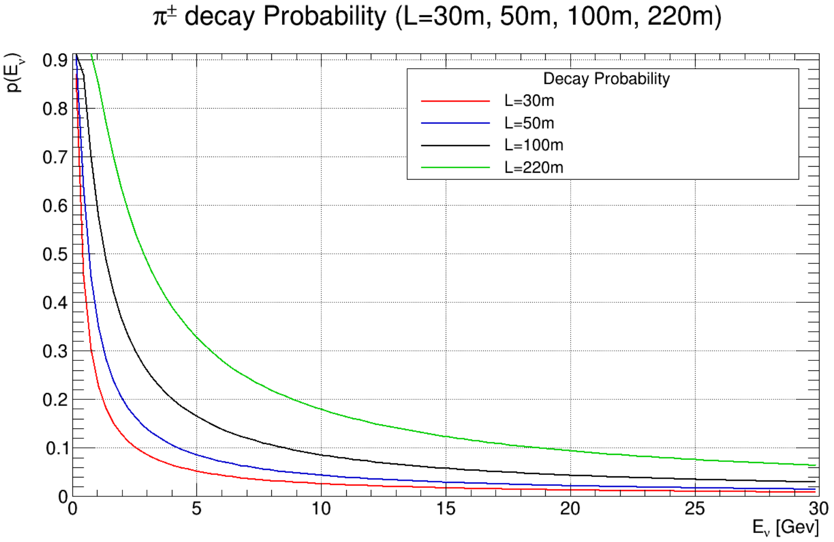

Figure 3.3: Comparison of decay probability of mother-charged pions for various distances between the target and 3D dipole

These plots show that the shorter the distance charged pions travel, the less their decay probability before passing through the 3D dipole. This implies that more neutrinos will be able to reach the neutrino detector. Hence, higher neutrino flux and less neutrino background for dark matter searches. Also, the signal flux is directly proportional to the energy of the charged mother pions as more of these particles can pass through the 3D dipole.

As for the signal flux, we know that,

$$\text{Signal flux} \propto \frac{1}{(distance\ travelled)^2}$$

$$S_{NRHF} = S_{DUNE}\left[\frac{L_{ND}}{L_{DM}}\right]^2$$

where L_{ND} is the distance between the target and ND in DUNE and $L_{ND} = 574$ m, L_{DM} is the distance between the target to DM detector.

The neutrino background flux in NRHF can be written as:

$$B_{NRHF} = N_{\pi}\, E_{\pi^{\pm}}\, [1 - \, p_{NRHF}(E_{\pi^{\pm}})] = B_{NE}\, \frac{1 - p_{NRHF}\left(E_{\pi^{\pm}}\right)}{1 - p_{NE}\left(E_{\pi^{\pm}}\right)}$$

The signal-to-background ratio with respect to DUNE is

$$\frac{S_{NRHF}}{\sqrt{B_{NRHF}}} = \; f_{en}(L, E_{\nu})\, \frac{S_{DUNE}}{\sqrt{B_{DUNE}}} = (\frac{574}{L_{DM}})^2 \sqrt{\frac{1-\exp[-b(E_{\nu})L_{NE}]}{1-\exp[-b(E_{\nu})L_{NRHF}]}}\frac{S_{DUNE}}{\sqrt{B_{DUNE}}}$$

Additionally, the NRHF signal-to-background enhancement factor with respect to DUNE ND can be written as follows:

$$f_{en}(L, E_{\nu}) \; = \; (\frac{L_{ND}}{L_{DM}})^2 \sqrt{\frac{1-\exp[-b(E_{\nu})L_{NE}]}{1-\exp[-b(E_{\nu})L_{DM}]}}$$

where L_{NE} is length of the charged meson decay pipe and $L_{NE} = 220\ m$

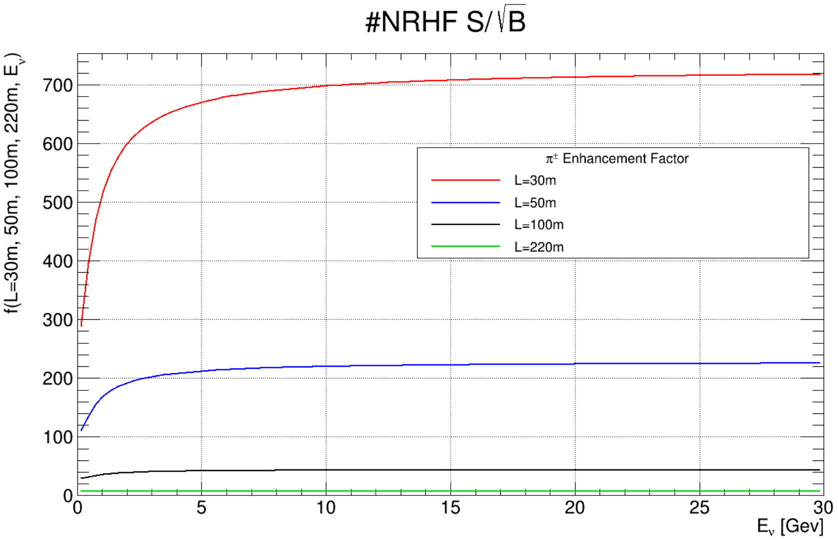

Figure 3.4: Signal-to-background ratio between NRHF system and DUNE for different distances of L_{DM}

3.3 DUNE-NRHF Flux Comparison

Next, we converted the GEANT4 [12] generated DUNE neutrino flux data into NRHF neutrino flux. Basically, neutrino flux is determined by the decay of the mother-charged pions. We have already derived the formula for the decay probability of charged pions as a function of neutrino energy.

$$1- p\,(E_{\nu}) = 1-\exp[-b(E_{\nu})L]$$

where boost factor [b (E_{ν})] = $-\frac{0.018\,L}{\sqrt{4E_{\nu}{}^{2}-(0.14)^{2}}}$

For the data conversion from DUNE to NRHF, we take the distance from the carbon target to the 3D dipole to be 50 meters. Next, we took the neutrino energy from DUNE data and substituted it in the above equation. This way, we have a new decay probability in NRHF. After that, we multiplied DUNE flux data with decay probability for each corresponding neutrino energy. This way, we have a new set of neutrino flux data for the NRHF system.

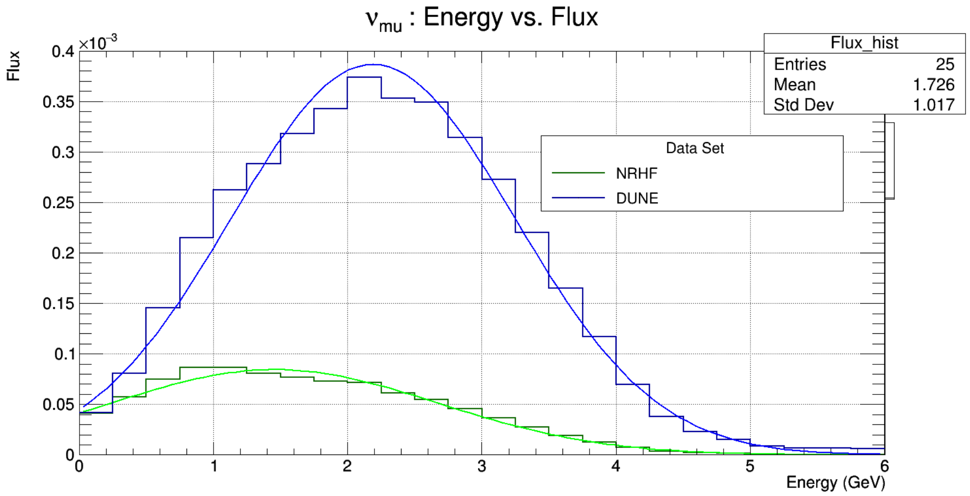

Figure 3.5: Neutrino flux comparison between NRHF system DM detector section and DUNE

The blue histogram represents the neutrino energy spectrum in DUNE, while the green represents the NRHF system’s neutrino energy spectrum. The blue fit line is a gaussian curve that describes the neutrino energy spectrum in DUNE, while the green fit lines portray the neutrino energy spectrum of the NRHF system.

From this plot, we can observe less neutrino flux in the NRHF system than in DUNE for the same neutrino energy. This result indicates we have less neutrino background for the LDM signal search.

Similarly, we took the survival probability equation, estimated the neutrino flux in NRHF for the neutrino experiment section, and compared it with DUNE data. We observed neutrino fluxes of similar magnitude between NRHF and DUNE. The blue histogram represents the neutrino energy spectrum in DUNE, while the green represents the NRHF system's neutrino energy spectrum. The blue fit line is a gaussian curve that describes the neutrino energy spectrum in DUNE, while the green fit lines portray the neutrino energy spectrum of the NRHF system.

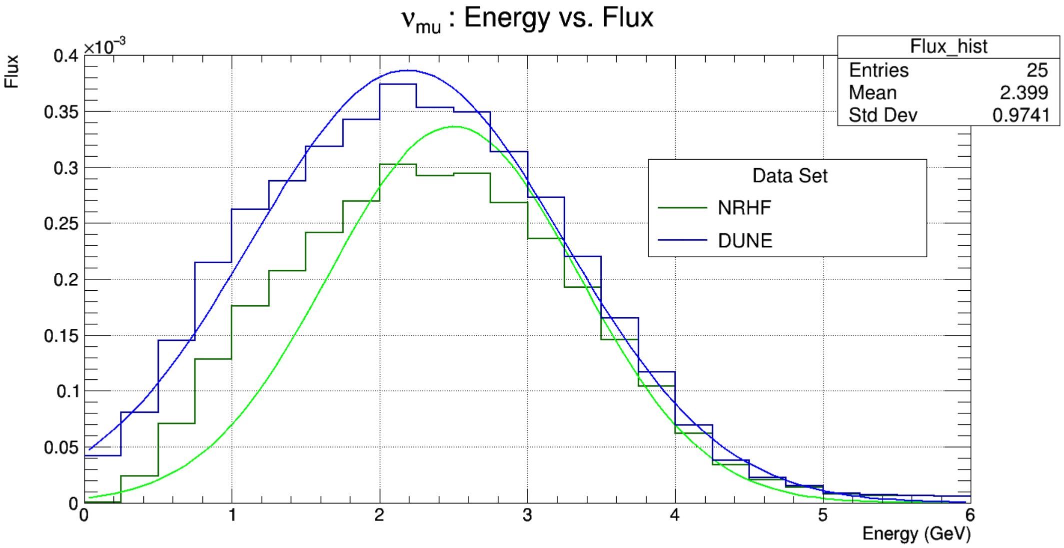

Figure 3.6: Neutrino flux comparison between NRHF system neutrino experiment section and DUNE

CHAPTER 4

TARGETLESS DUNE

4.1 Working Mechanism

Targetless DUNE follows a similar principle as that of DUNE. The primary idea of this framework is to eliminate the carbon target and meson decay pipe, and direct the proton beam onto the beam dump. With that, charged particles will be absorbed as soon as they are generated without any chance to decay and produce neutrinos. This way, we substantially reduce the neutrino background. Another benefit of this configuration is by having a hadron observer as a target, we can have an intense dark matter beam as the beam dump is nearer to the Near Detector. The distance between the target and the detector is ~ 574 m, and for the dump and the detector is ~304 m.

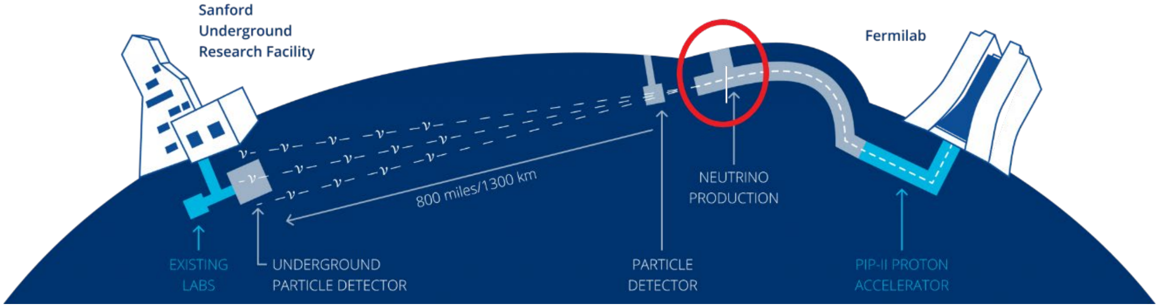

Figure 4.1: Overview of Target DUNE framework where the initial carbon target (area in red circle) is removed

As in the DUNE framework, we start with an accelerated, high-intensity proton beam. This beam will hit the beam dump, and the interaction will give out elementary particles, such as charged pions ($\pi^{\pm}$), neutral pions (π^{0}), kaons (K), electrons (e^{-}), highly energetic photons (γ), and LDM (photons coupling into dark photon and annihilate into two LDM particles). Most particles, including charged pions, will be instantly absorbed instead of decaying. Hence, the neutrino background will be substantially reduced compared to the original DUNE configuration.

4.2 Simulation Parameters and Data Analysis

We used the GEANT4 simulation kit to simulate interaction in this configuration. As discussed above, we removed the carbon target and made a new target out of the cubical DUNE beam dump. It is made up of an aluminum core covered by steel blocks of a volume of 4 x 4 x 4 meters. To absorb the particles produced from the interaction of the beam remnants, the steel blocks were extended out 3 m from the beam axis to 7.8 m.

As for the physics lists of GEANT4 source code, we used `G4EmStandardPhysics` for the electromagnetic interactions and `QGSP BIC AllHP` for the hadronic reactions. For tracing and recording all charged mesons in the proton interaction, an inherited user-defined class of `G4UserSteppingAction` was developed, which was derived from `G4SteppingAction`. We recorded the four-momenta of all the neutrinos produced by the decay of charged meson in the simulation.

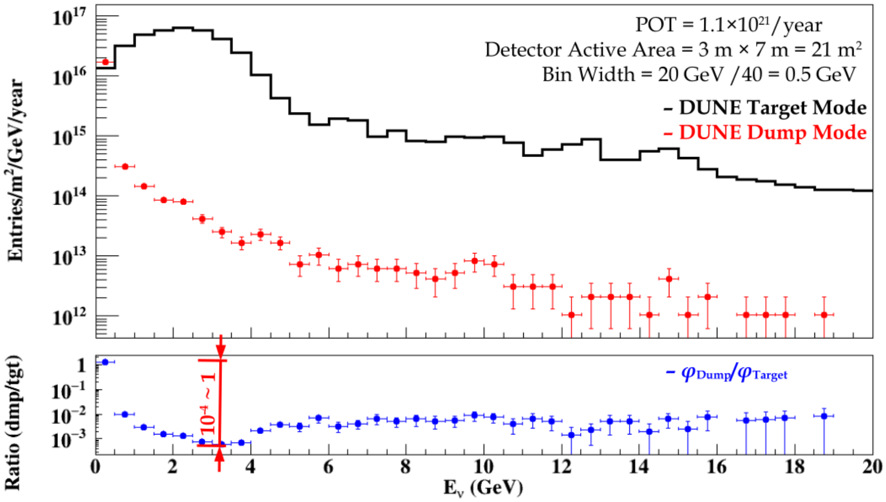

Figure 4.2: Comparison of Neutrino fluxes in DUNE and Targetless DUNE at the beam dump

We can see how removing the target and impinging the proton directly into the beam dump can significantly reduce the neutrino fluxes. This way, we can have a relatively background-free configuration for LDM searches.

CHAPTER 5

CONCLUSION DISCUSSION

The study of neutrinos is definitely one of the ways to extend our current understanding and dive into the BSM world. Large-scale experiments such as DUNE will help us examine these elusive particles and could provide answers to many unknown questions, as described in Chapters 1 and 2. In this configuration, there is also a possibility to look for particles like LDM. However, the central issue of looking for LDM in neutrino experiments is that the neutrinos will be the primary background for the dark matter signal. This is because the LDM signal will look very similar to the neutrino interaction signal. Hence, minimizing the neutrino flux will be the highest priority.

One of the ways to reduce background neutrinos is by using the sign-selecting 3D dipole, as discussed in Chapter 3. By diverting the charged particles after they are produced in proton interaction, we will be able to minimize the neutrino background and increase the LDM signal by 2 to 4 orders of magnitude. At the same time, we can also have a similar flux number as DUNE in the NRHF neutrino experiments section. This configuration allows the coexistence of dark matter and neutrino experiments in a single framework. Additionally, we do not have to deal with un-interacted protons and neutral mesons, which are an additional source of systematic uncertainties in the LDM search.

Another way to minimize the neutrino production number in DUNE-like experiments is by reducing the neutrino target, as shown in Chapter 4. Removing the carbon target at the front and having the proton interact directly with the beam dump can significantly minimize the neutrino number for BSM particle search, as shown in Figure 4.2.

In conclusion, neutrino physics has entered the high precision measurement era, and we can expect to see lots of development in the neutrino sector in the coming years. With the possibility of finding answers to various problems unexplored by the Standard Model, we live in a fantastic time to study these elementary particles – neutrinos!

APPENDIX A

LIST OF SYMBOLS

n	Neutron
p^+	Proton
e^-	Electron
μ	Neutrino
$\bar{\nu}$	Anti-neutrino
$\bar{\nu}_e$	Anti-electron neutrino
$\pi^\pm$	Charged pion
π^0	Neutral pion
K	Kaon
η	Eta
γ	Photon
μ	Muon

APPENDIX B

NOMENCLATURE

DUNE	Deep Underground Neutrino Experiment
DM	Dark Matter
LDM	Low-mass Dark Matter
BSM	Beyond the Standard Model
CP	Charge-conjugation and Parity-reversal
ND	Near Detector
FD	Far Detector
NRHF	Neutral Rich Horn Focusing

REFERENCES

[1] Planck Collaboration doi-10.1051/0004

[2] Y. Fukuda et al. (Super-Kamiokande Collaboration) Phys. Rev. Lett. 81, 1562 (1998)

[3] C.L. Cowan, F. Reines, F.B. Harrison, E.C. Anderson and F.N. Hayes, Science 124 (1956) 103.

[4] D. Kirkby, and Y. Nir "CP VIOLATION IN MESON DECAYS," Weizmann Institute. 1 (2009)

[5] Fukugita, M. & Yanagida, T. Baryogenesis without grand unification. Phys. Lett. B 174, 45–47 (1986).

[6] Acero, M. A. et al. First measurement of neutrino oscillation parameters using neutrinos and antineutrinos by NOvA. Phys. Rev. Lett. 123, 151803 (2019).

[7] B. Batell, M. Pospelov and A. Ritz, Exploring Portals to a Hidden Sector Through Fixed Targets, Phys. Rev. D 80 (2009) 095024, [0906.5614].

[8] P. deNiverville, M. Pospelov and A. Ritz, Observing a light dark matter beam with neutrino experiments, Phys. Rev. D 84 (2011) 075020, [1107.4580].

[9] B. Dutta, D. Kim, S. Liao, J.-C. Park, S. Shin and L. E. Strigari, Dark matter signals from timing spectra at neutrino experiments, Phys. Rev. Lett. 124 (2020) 121802, [1906.10745].

[10] L. Buonocore, C. Frugiuele and P. deNiverville, Hunt for sub-GeV dark matter at neutrino facilities: A survey of past and present experiments, Phys. Rev. D 102 (2020) 035006, [1912.09346].

[11] B. Dutta, D. Kim, S. Liao, J.-C. Park, S. Shin, L. E. Strigari et al., Searching for Dark Matter Signals in Timing Spectra at Neutrino Experiments, 2006.09386.

[12] S. Agostinelli, et al./ Geant4—a simulation toolkit, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 506, Issue 3, 2003

BIOGRAPHICAL INFORMATION

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Apart from academics, he is interested in literature, music, astrophotography, and solo hiking/camping.